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Intensity Improvement For AD Experiments Using Barrier Bucket Cooling

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Abstract

We propose to cool the antiproton beam confined into a 300 ns or shorter barrier bucket. The longitudinal emittance obtained this way is much smaller than it is possible with coasting beam cooling. This allows beam bunching already in the AD ring with 202.56 MHz, the frequency of the ASACUSA RFQD. The proposed scheme requires the installation of two 202.56 MHz cavities and a barrier bucket cavity into the ring. With this modest investment ASACUSA gains a factor 2-3 in intensity. A proof of principle test has been done during 3 MD sessions recently. The beam emittances in all planes were measured after the beam was cooled in the barrier bucket and were found sufficiently low.

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Intensity Improvement For AD Experiments Using Barrier Bucket Cooling

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I. INTRODUCTION

The beam temperature is directly related to the particle velocities in the moving frame and the velocities are related to the focusing forces in each plane. The higher the focusing force the higher the particles velocity in that plane. Electron cooling is based on the temperature exchange between the hot ion beam and the cold electron beam. When the equilibrium temperature is reached, a beam confined into a small part of the machine circumference will have a smaller longitudinal emittance than a coasting beam with a similar momentum spread. In the AD at present a coasting beam is cooled, although there is some overlap between the cooling and RF capture processes.

There is a limit however how much the beam can be confined. The intra beam scattering and the space charge forces have to be considered. Even the intensity in AD is low, about 3.5×10^7, at small emittances both effect can be significant.

We propose to confine the beam into a 300 ns or shorter barrier bucket (BB from here) and cool it. This allows a gain of several factors in longitudinal emittance compared to the present scheme. Then the beam is captured with two 202.56 MHz cavity in the AD ring and extracted towards the RFQD.

A. The present scheme

At present a coasting beam is cooled, then bunched with V_{rf}= 500V at harmonic one. Then an optional bunch rotation is applied. The beam is transported at 5.3 MeV kinetic energy to the experiments. ATRAP and ALPHA use degrader foils to decelerate it further to a few KeV. Only a small fraction of the pbars ejected from the AD is trapped, around 0.1%. ASACUSA uses an RFQD to decelerate from 5.3 MeV to a kinetic energy adjustable between 10-120 KeV. There is a buncher cavity 6 meters front of the RFQD. This is necessary to introduce the 202.56 MHz bunch structure required by the RFQD. That kind of bunching puts a 50% theoretical limit to the RFQD deceleration rate and increases the momentum spread. In practice only about 25 % is decelerated. ASACUSA uses also a degrader foil for vacuum isolation, but a very thin one. Using the RFQD about 4 % of the pbars ejected from the AD is trapped, this is much better than using only a degrader foil. Sharing the RFQD between the experiments is not possible in the present scheme due to the large dp/p at the exit of the RFQD, it is about 3×10^{-2} at 100 KeV. The beam can't be bended with this large dp/p without severe losses.

B. The proposed scheme

We propose to cool the beam in a 300 ns long BB, the maximum length the experiments can except or shorter. The longitudinal emittance of the beam in the BB is much smaller than the value obtained with coasting beam. Then the beam is bunched with the RFQD frequency, 202.56 MHz. The 300 ns long train of bunches is ejected from the AD and sent to the RFQD. The buncher cavity before the RFQD will be still used to compress the beam into the ± 10 degrees phase acceptance [1]. Although it would be better to compress the beam adiabatically into the phase acceptance already in the AD, this is not possible due to the longitudinal space charge forces. Also the longitudinal tune would be very high. With a ± 10 degrees phase acceptance of the RFQD the buncher cavity can not be avoided. The buncher will give about $\pm$ 50-100 KeV longitudinal kick to the outermost particles. The kick due to the buncher will dominate the energy spread of the beam entering the RFQD, because the beam ejected from the AD has only $\pm$ 5 KeV energy spread in the new scheme. The momentum spread at the exit of the RFQD therefore is similar to the present scheme. We gain a factor 2-3 in intensity for ASACUSA due the bunching with 202.56 MHz in the AD ring. Fig.(1) shows clearly where this intensity gain comes from. The 202.56 MHz bunching in the AD is possible, because the longitudinal emittance is much smaller when the beam is cooled in a BB.

With the present instrumentation we can't observe very short bunches. It would be very useful to see the 202.56 MHz beam structure. A wall current monitor or a fast transformer has to be installed in the ring to do that. The peak current is low in the AD, but still can produce a voltage on 50 Ohm well above the thermal noise level.

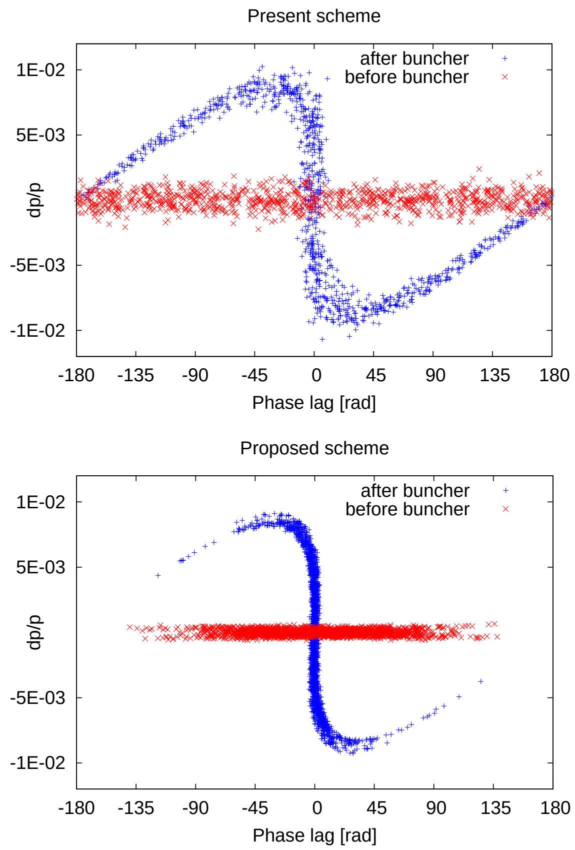

FIG. 1: Phase space plot before and after the RFQD buncher cavity in the present and in the proposed scheme. At present only 30 % of the beam is inside the RFQD phase acceptance ($\pm$10 degree). In the proposed scheme this number is 86 %.

II. DISCUSSION

A. IBS and tune shifts

We will consider different effects that might cause problems for the barrier bucket cooling or for the capture process.

The scattering due to residual gas acts on individual particles and the barrier bucket makes no difference. The intra beam scattering (IBS from now) is higher when the beam is confined into a BB, also the incoherent tune shift due to space charge. The tune shift for a bunched beam can be calculated with the following formula:

$$\Delta Q_y = -\frac{2LNR_p}{L_b \pi \beta^2 \gamma^3 \left(\sqrt{\frac{\epsilon_x}{\epsilon_y}}+1\right)\epsilon_y} \tag{1}$$

Where L is the AD circumference, R_p is the pbar radius, L_b is the bunch length, and N is the number of pbars in a single bunch. With 3.5×10^7 total number of particles in the machine and 1π mm mrad emittance in both transverse planes, 300 ns long train of bunches and $\pm$70 degrees phase extent of the bunches, the tune shift is -0.073 . This is already an acceptable value, but in our case the tune shift has no time to make harm, because the bunching process is very fast due to the high harmonic number. The bunching process lasts only 107 turns and only during the last few turns the beam has this tune shift. The tune shift in the barrier bucket will be much smaller than we calculated above, it will not be a problem.

We don't have to worry about IBS for the bunched beam for the same reason, the 202.56 MHz bunch structure is present only for a very short time in the AD. The IBS has been calculated by MAD-X [3] using the standard AD optics at 100 MeV/c for a coasting beam. Table I. shows the values. Since the beam in a BB is a confined coasting beam, we can calculate the IBS by multiplying the values for the coasting beam by the confinement factor 19, which is the ratio between the revolution time and the duration of the BB. It is reasonable to assume that

	longitudinal	horizontal	vertical
Coasting beam	68	79	-2910
Barrier bucket	3.58	4.16	-153

TABLE I: Lifetimes in seconds for coasting beam with intensity 3.5×10^7 and the beam in a 300 ns long barrier bucket, calculated by the MAD-X IBS module. We assumed dp/p= 1×10^{-4} and 1π mm mrad transverse emittances in both cases.

the emittances in the BB will be determined by an equilibrium between the IBS and the cooling force. The IBS allows transverse emittances well below 1π mm mrad.

B. Cooling in the barrier bucket

Particles in a BB usually are not exposed to longitudinal forces, only for a short time at the barrier. The barrier is typically created by two pulse across a gap, separated in time with some delay. This creates longitudinally stable and unstable regions around the machine. The particles inside the unstable region drift into the stable region after certain time and stay there. Significant portion of the beam has very low momentum spread. The time it takes for particles with dp/p $< 10^{-5}$ to get into the stable region is long, it is in the order of a second. Due to this long shifting time moving barriers must be used. At the begining the barrier pulses has zero separation and the amplitude of the pulses are increased adiabatically. At the end of the voltage increase most of the machine circumference contains particles, except at the position of the barrier pulses. Then the pulse separation is increased until the bucket becomes 300 ns long. The BB capture is illustrated in Fig.(2). Without electron cooling this would increase the momentum spread by a factor, which is the ratio between the machine circumference and the BB length. With electron cooling the momentum spread is kept at a low value, giving a much smaller longitudi-

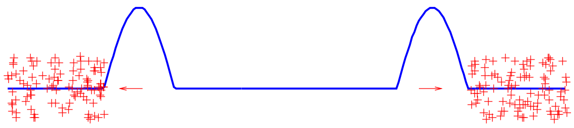

FIG. 2: Capture with moving barrier bucket. The barrier pulse is a half sine wave.

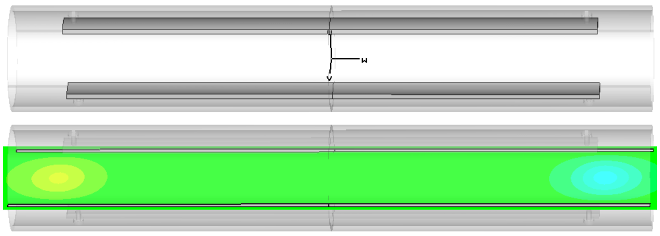

FIG. 3: The dumper structure (top) and the longitudinal component of the electric field indicated by colors (bottom).

nal emittance. This is actually the main idea behind this proposal. In a low intensity machine like the AD this is possible, because the IBS and the space charge effects remain acceptable even the beam is compressed by a large factor.

The BB cooling has been tested with the existing hardware during 3 MD sessions recently. There is a transverse damper system in AD used only for tune measurements at the moment. The damper kickers are 1 meter long 50 Ohms stripline pairs driven by 100 W RF amplifiers. The amplifiers have been replaced by a more powerful one used in the PS damper system, capable of giving 1500 W. Normally the driving currents have a 180 degrees phase difference, giving a transversely deflecting EM field. If the barrier pulses are in phase on the two electrodes, there are longitudinal components at the entry and the exit of the kicker. A 15.9 MHz half sine wave was used as a barrier pulse with an amplitude of 250 V. An arbitrary waveform generator has been programmed to provide the BB pulses. The two barrier pulse had the same polarity, because the longitudinal electric field has opposite direction at the ends of the damper kicker as shown on Fig.(3). The transverse emittances has been measured by the fast scrapers and found to be well below 1 π mm mrad with a tail structure we also observe with a coasting beam. When the two amplifiers driving the damper were not well balanced or when the barrier voltage was higher, the transverse emittances were worse. This suggests the damper kicker had a significant effect on the transverse planes. Using a proper BB cavity the transverse emittances might be better than it was measured in this proof of principle test.

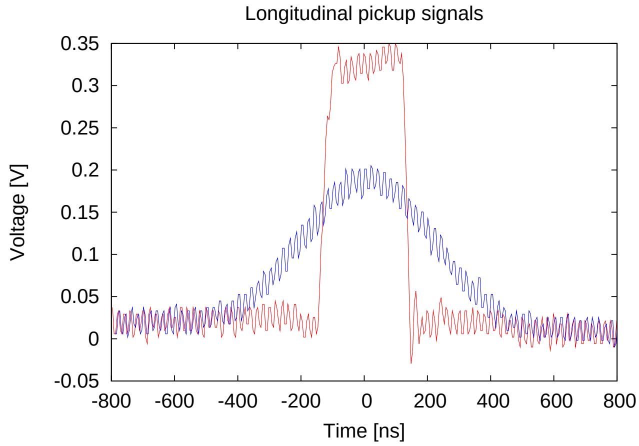

FIG. 4: Waveforms recorded during the dp/p measurement in the BB. The red trace is the beam on the longitudinal pickup, when the BB voltage was turned off. The blue trace was recorded 347 turns later.

The momentum spread of the beam after the BB cooling was calculated from a measurement on a longitudinal pickup. An OASIS scope was triggered when the barrier voltage was turned off, and several hundred turns was registered at high sampling rate. From the shape of the diffusion the dp/p was calculated and found to be between 1-1.5 10^{-4}. This is low enough to allow the capture with 202.56 MHz in the AD ring. Fig.(4) shows the recorded waveforms.

The emittance measurements were repeated with a 160 ns long BB. The transverse emittance values were a bit higher, but still below 1 π mm mrad. It looks very much feasible to use a shorter BB length than 300 ns.

C. The capture with 202.56 MHz

Capturing the beam in the AD with 202.56 MHz gives a harmonic number 1160. Due to the high harmonic number the momentum acceptance is low. It is easy to see, if the particle drifts a distance (compared to the synchronous particle) bigger than the length of the RF bucket between two longitudinal kicks, it will go out of the bucket. This can't be cured by increasing the cavity voltages, only by increasing the number of cavities in the ring. That is one reason we need two cavities in the proposed scheme. The simulations showed the dp/p has to be smaller than 6×10^{-4} with two cavities in the ring.

The longitudinal phase space ellipse is not standing straight at the cavities, but only half way between them. This is a consequence of the high harmonic number. Ideally the beam should arrive at the RFQD buncher cavity standing straight. This can be achieved by choosing the position of the cavities accordingly. The high harmonic number allows a fast capture process and a small dynamic range. The starting voltage doesn't need to be very low.

During the capture process with 202.56 MHz, the longitudinal space charge forces become important. The capture process needed simulation, because of the high synchrotron tune, the low momentum acceptance and the longitudinal space charge forces. The simulation was done with a program developed earlier by the author [2] and it was extended to include the longitudinal space charge forces. The longitudinal electric field inside a bunch can be calculated as:

$$E_z = \frac{(1 + 2ln(\frac{b}{a}))}{4\pi\epsilon_0\gamma^2}\frac{d\lambda}{dz} \tag{2}$$

Where b is the radius of the vacuum chamber and a is the radius of the beam, λ is the charge density function. The λ is not known for advance. It is calculated by partitioning the bunch along the longitudinal position into bins and counting the number of particles in each bin. Cubic spline fitting was used to obtain a smooth function.

The capture process has been simulated with two 202.56 MHz cavities in a dummy ring having the same circumference as the AD. The voltage was increased from the initial 50 Volt to 12 kV adiabatically. For the calculation of the cavity voltage function the AD RF Cycle Editor algorithm was used, with an adiabatic constant k=0.3. The capture process takes 107 turns. Fig.(5) shows the phase space plot and the charge density distribution for the last turn. The total voltage of the two cavities at the last turn is 12 kV.

There are suitable cavities available at CERN which can be used for our purpose. Two 200 MHz cavities has been taken out from the PS. These can be installed in the AD ring. The resonant frequency is a bit lower than 202.56 MHz, but they are manually tunable by pistons. The frequency can be increased to 202.56 MHz without much difficulty. The original 25 KW amplifiers are not available, therefore two amplifiers has to be built or bought. These amplifiers should be much smaller and cheaper than the PS amplifiers, because the duty factor is very low in the AD. The capture process is only 6 μs long. The cavities have large apertures, the radius is about 10 cm. The structure is not under vacuum. The gap is a ceramic insertion in the vacuum pipe. Due to the high frequency of the cavities and the low β which is about 0.1 at 100 MeV/c, the transit time factor in the AD will be very low. We need to keep the radius of the beam pipe inside the cavity as low as possible to maximize the transit time factor. With bigger aperture the RF field has a bigger longitudinal extent, that makes the transit time factor worse. At injection energy we need to keep an acceptance about 220 π mm mrad and the maximum β function is about 9 meters at the planned location of the cavities. This gives 5 cm for the radius of the vacuum pipe. The ceramic insertion used in the PS is much bigger than that, two new ceramics has to be ordered. With 5 cm radius, the transit time factor is 0.37. This is low, but the maximum voltage needed also low, only 6 kV for each cavity. These cavities are able to give 50 kV, so even with this low transit time factor there is a comfortable margin.

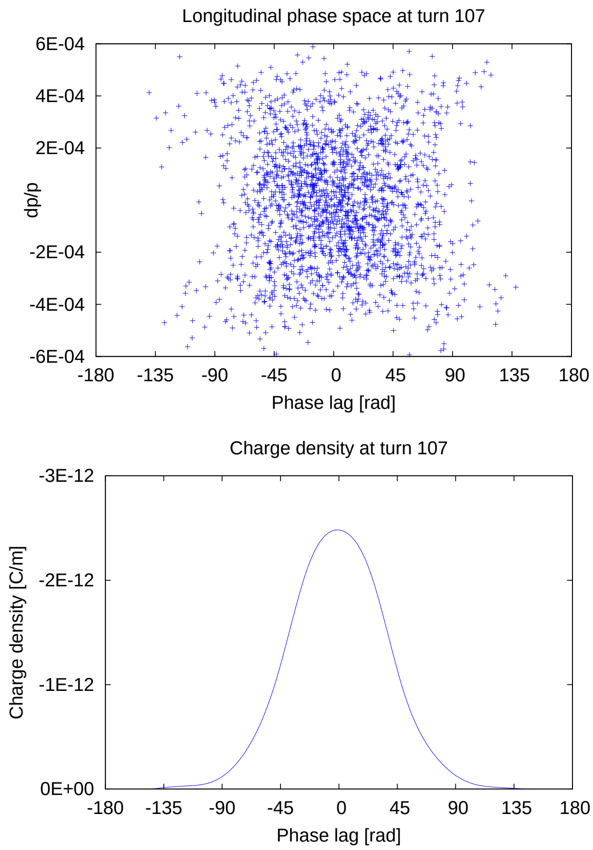

FIG. 5: Phase space plot and charge density distribution at the end of the capture process. The starting dp/p was 1.5×10^{-4}

The RFQD, the 202.56 MHz cavities in the AD ring, the ejection kicker and the BB waveform must be synchronized together. This could be assured by using the 202.56 MHz signal coming from the RFQD low level system as the clock signal for the arbitrary waveform generator producing the BB waveform. The same signal should drive the cavities in the AD ring. The RFQD must be the master, because to achieve its best performance it has to be tuned on resonance. The maximum slow drift of the RFQD frequency is about 100 kHz. It could be reduced if needed by keeping its temperature constant. The ejection kicker timing should be also derived from the RFQD frequency.

The cavities have to be placed into the AD ring such, that their distance is the half circumference of the AD ring. Also the cavity which is upstream to the ejection septum should ideally be a quarter AD circumference away from the RFQD buncher cavity, so the bunch would arrive standing straight at the buncher. This second requirement can't be fully satisfied due to lack of free space in the AD ring. The buncher is 12 meters farther than it would be ideally, but the penalty in terms of intensity is negligible.

The cavities can be put in the dispersion free regions where at the moment the damper kickers and pickups are. The damper kickers are used only for tune measurement and the pickups are not used at all. The damper kickers and pickups have the same geometry, they can be used as kickers or pickups. One cavity could be put at the place of the vertical kicker named DR.DAV1605. The other can be put at the place of the horizontal damper pickup named DR.USH4405. Removing DR.DAV1605 and DR.USH4405 from the ring we still have a horizontal damper kicker and the vertical damper pickup named DR.USV4407. That can be used as vertical kicker, so the BTF tune measurement can be done. At the position of the DR.USH4405 there is enough space to put the barrier bucket cavity too.

D. Moving forward

Here we make a list of things need to be done to put the proposed scheme operational.

- Installation of the 202.56 MHz cavities into the AD ring.
- Fabrication of two new piece of vacuum chamber including the ceramics for the cavity gaps.
- Construction of two power amplifiers to drive the cavities. Maybe these can be bought off shelf.
- Design and installation of a new barrier bucket cavity. This cavity will have very low duty cycle. It will dissipate only a few times 10 W, it should be easy to do. The PS damper amplifier can be used to drive it. The PS amplifier has two channels, we need only one channel. Maybe a new single channel version of this amplifier should be built.
- A wall current monitor or other instrument able to observe the 202.56 MHz beam structure has to be installed into the AD ring. This need to be investigated further.
- Two (one for operation and one spare) arbitrary waveform generator card need to be bought. The instrument which was used for the MD exists in a cPCI form factor. Using it would minimize the software development, because most of it has already been developed for the MD.
- Working out the details and installing the hardware for the timing and synchronization of the ejection kicker with the 202.56 MHz bunches. This probably could be done using standard CO and RF hardware.

III. CONCLUSIONS

There are two main elements of this proposal. One is to cool the beam in a barrier bucket, then capture it with 202.56 MHz. The first leads to a large reduction of the longitudinal emittance and makes the capture with 202.56 MHz in the AD ring possible. This requires the installation of equipment into the ring and some additional work. We propose to do the installations during the 2009 shutdown. The new scheme allows a factor 2-3 gain in intensity for ASACUSA or other experiments if they work with a 202.56 MHz RFQD. The barrier bucket capture and cooling has been tested successfully with the existing equipment during the 2009 run. Many equipment needed for the proposed scheme are available at CERN or can be built. At this stage an accurate cost estimate can't be given. We have shown in this paper the feasibility of the proposal. The participation of the support groups are essential to move forward with the implementation.

IV. ACKNOWLEDGMENTS

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[1] A.M. Lombardi, W. Pirkl, Y. Bylinsky, "First Operating Experience with the CERN Decelerating RFQ for Antiprotons", CERN-PS-2001-064-PP.

[2] L. Bojtár "Transverse-Longitudinal Emittance Transfer in Circular Accelerators Revised", CERN-AB-Note-2008-027.

[3] MAD-X, "http://mad.web.cern.ch/mad/"